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Chapter 2

Author's contribution to Chapter 2: First to identify the Albion Formation as Chicxulub ejecta blanket deposits in Belize. Lead scientific expeditions to conduct fieldwork, collected samples, mapped Albion quarry, developed stratigraphical column, collected striated boulders, identified Spheroid Bed, analyzed and photographed thin section, conducted SEM study, and proposed depositional model.

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Ejecta blanket deposits of the Chicxulub crater from Albion Island, Belize

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Ejecta blanket deposits of the Chicxulub crater from Albion Island, Belize

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ABSTRACT

An extraordinary deposit disconformably overlies Late Cretaceous dolomite on Albion Island in northern Belize. The basal unit is a 1-m-thick bed of clay-rich dolomite and calcite silt containing abundant 1- to 20-mm-diameter spheroids of dolomite and spheroidal to angular clasts of clay containing relict vesicles. Both the dolomite and clay spheroids are flattened near the basal contact. This spheroid bed is overlain by 15 m of diamictite that contains millimeter- to meter-sized clasts (maximum 7.5 m) floating in a matrix of dolomite silt. The clasts are mostly dolomite but include limestones with Early to Middle Cretaceous rudists and foraminifera. Clasts are commonly fractured and range from well-rounded pebbles and cobbles to highly angular flakes. Polished facets and multiple sets of striations on single clasts indicate severe abrasion. The diamictite bed also contains abundant clay clasts with relict vesicles as well as mud balls, pockets of calcite pisoids, and authigenic quartz. Metamorphic rocks and detrital quartz are restricted to rare sand-size chips found in insoluble residues.

We propose that the Albion Island deposits are the most proximal, exposed section of ejecta from the Chicxulub crater yet found. The Albion spheroid bed is similar to spherule beds described from elsewhere in the Gulf Coast and Caribbean region, but the dolomite spheroids are thus far unique and may be the tektite-equivalent of vaporized carbonates. The only correlate for the Albion diamictite is the coarse ejecta unit drilled on the rim of the Chicxulub crater. The Albion diamictite shares many characteristics with the Bunte breccia of the Ries crater. We propose that the spheroid bed was deposited by the vapor plume and the diamictite by ballistic sedimentation coupled with debris flow processes.

INTRODUCTION

An iridium-rich ejecta deposit at the Cretaceous/Tertiary (K/T) boundary lead Alvarez et al. (1980) to propose that the impact of a comet or asteroid 65 m.y. ago caused the mass extinction recorded at this geological boundary. Subsequent studies throughout the world have identified impact ejecta deposits at the K/T boundary. The recent recognition that the proposed K/T impact formed the Chicxulub crater in the northern Yucatán Peninsula (Hildebrand et al., 1991; Pope et al., 1991) has focused research on the Gulf of Mexico–Caribbean region. It is in this region that the ejecta deposits are thickest and K/T tektites are largest, and it is here that impact-wave deposits have been inferred (e.g., Smit and Romein, 1985;

Ocampo, A. C., Pope, K. O., and Fischer, A. G., 1996, Ejecta blanket deposits of the Chicxulub crater from Albion Island, Belize, *in* Ryder, G., Fastovsky, D., and Gartner, S., eds., The Cretaceous-Tertiary Event and Other Catastrophes in Earth History: Boulder, Colorado, Geological Society of America Special Paper 307.

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Bourgeois et al., 1988; Hildebrand and Boynton 1990; Izett, 1991; Maurrasse and Sen, 1991; Alvarez et al., 1992; Smit et al., 1992; Pitakpaivan et al., 1994).

In this chapter we report findings from a K/T boundary section located in a quarry on Albion Island, Belize, which at only 364 km from the center of the Chicxulub Crater (Fig. 1) is the most proximal ejecta exposure yet known. The Albion Island section provides an example of deposits intermediate between the crater rim (known only from drilling) and more distal ejecta, slumps, and impact-wave deposits.

REGIONAL GEOLOGY AND STRATIGRAPHY OF ALBION ISLAND

The geology of northern Belize is not well known because there is a paucity of good outcrops in this tropical, low-relief region and because weathering, solution collapse, and recrystallization of the carbonates and evaporites have destroyed much of the original textures, bedding, and fossils. Quarrying activity on Albion Island provides one of the best bedrock exposures in this region. The island was formed by a bifurcation in the Hondo River around a resistant carbonate block with local relief of about 60 m. The provisional geologic map of Belize (Fig. 2) identifies all of the carbonate rocks in this area as belonging to the Miocene to Pleistocene Orange Walk Group (Cornec, 1986), based primarily upon the work of Flores (1952). Uplifted blocks of Upper Cretaceous carbonates of the Barton Creek Formation are mapped 30 to 50 km south of Albion Island, along a series of northeast-southwest trending faults of the Río Hondo fault zone. Albion Island is located along one of these faults (Fig. 2). As we shall demonstrate, the island is also one of these uplifted blocks of Upper Cretaceous carbonate.

The regional stratigraphy (Fig. 3) has been established in a series of exploratory oil wells based upon the analysis of foraminifera and correlation of lithological units (Geology and Petroleum Office, 1986). The Remate well records place the K/T boundary at a depth of 375 m within dolomites equivalent in age to Barton Creek Formation (Fig. 3). The K/T boundary rises to a depth of about 190 m in the San Pablo 1 well, which is located 32 km southwest of Remate and 14 km northeast of Albion Island. The well at Blue Creek, 36 km southwest of Albion Island, encountered Cretaceous Barton Creek Formation at the surface, which contradicts the provisional geologic map (Fig. 2). The nature of the K/T boundary in these wells is uncertain, and some sections may not be complete. Micropaleontological studies of the Remate well suggest that the earliest Paleocene may be absent (Ramanathan, 1985), although no lithologic break is found. The Río Hondo fault zone appears to be a series of en

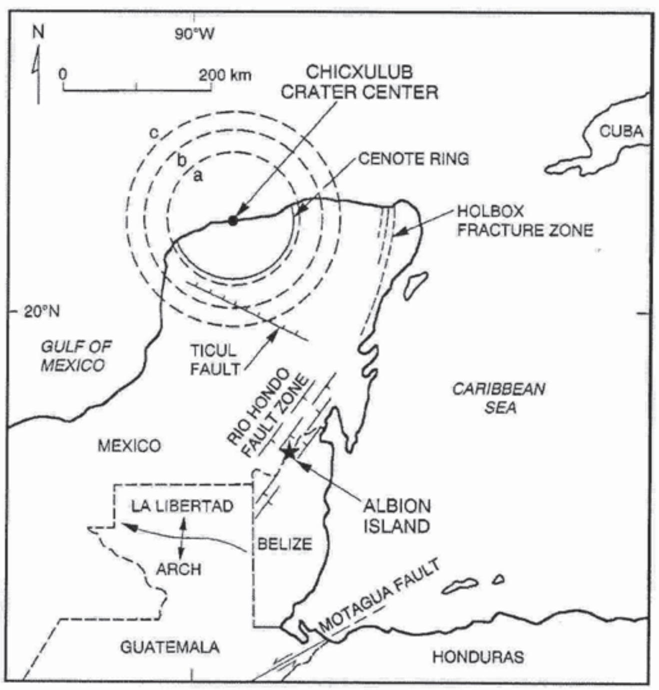

Figure 1. Map showing the location of Albion Island, Belize, with respect to the buried Chicxulub impact crater and other geological structures of the region. Dashed circles represent proposed crater diameters: (a) 180 km (Hildebrand et al., 1991; Pilkington et al., 1994), (b) 240 km (Pope et al., 1993), and (c) 300 km (Sharpton et al., 1993).

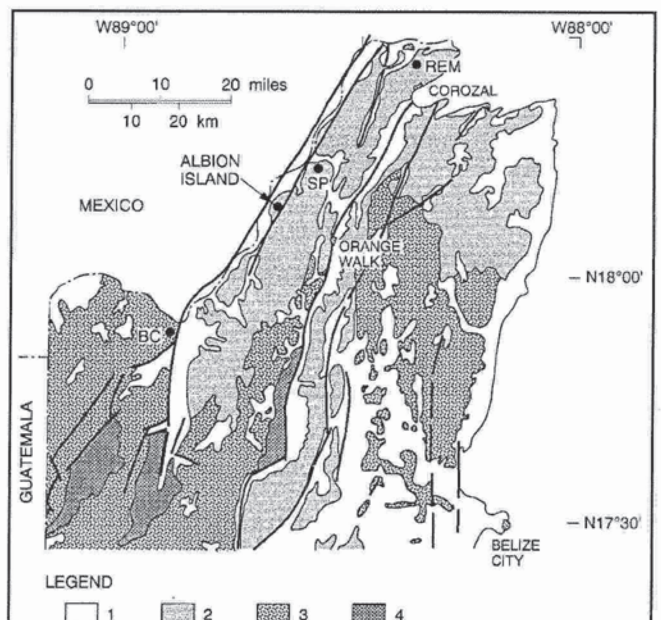

Figure 2. Geological map of northern Belize after Cornec (1986). Black dots mark exploratory oil wells and the Albion Island quarry shown in the cross section in Figure 3: REM—Remate; SP—San Pablo; BC—Blue Creek. Bold lines are faults. Key: (1) Quaternary carbonates and alluvium; (2) Miocene-Pleistocene carbonates and evaporites of the Orange Walk group; (3) Paleocene-Eocene carbonates of the Doubloon Bank group; (4) Upper Cretaceous carbonates and evaporites of the Barton Creek Formation.

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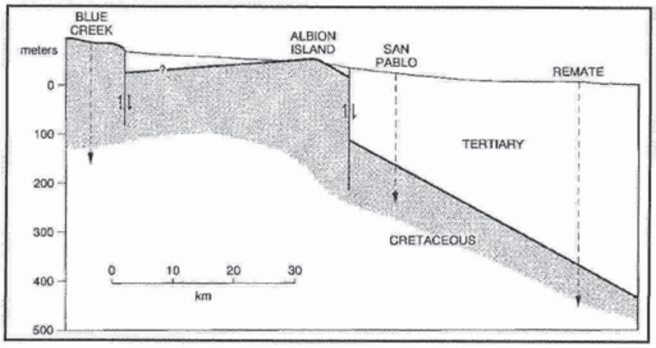

Figure 3. Geological cross section of northern Belize showing the location of the K/T boundary (bold line). Location of exploratory oil wells Remate, San Pablo, and Blue Creek is shown in Figure 2.

echelon faults with progressive uplift to the south and west; however, when this uplift occurred is unknown. Albion Island is the northernmost block with any significant relief.

The quarry on Albion Island exposes a 42-m-thick section (Figs. 4 and 5). A sharp disconformity separates the hard crystalline dolomites being quarried (Barton Creek Formation) from overlying clay-rich spheroid and coarse diamictite beds, here termed the Albion Formation. We propose that this disconformity marks the K/T boundary.

BARTON CREEK DOLOMITE

The basal portion of the Albion quarry section is composed of massive and thinly bedded, medium-crystalline dolomites, pale gray buff in color, such as is common through much of the Cretaceous of the region. Dark-gray laminations centimeters to millimeters thick are common, especially near the top. Thin sections indicate that the dark colors are due to organic matter and are associated with benthic foraminifera that are too poorly preserved for identification. The dolomites have been heavily recrystallized. Solution features including minor collapse breccias and rare clay layers are present. These rocks are typical of shallow and restricted carbonate platform deposits of the region.

We separated the dolomite from calcite in a foraminifera-rich dolomite sample from just below the proposed K/T boundary with dilute HCl for strontium isotope analysis. We conclude that the $^{87}Sr/^{86}Sr$ ratios reflect seawater compositions at the time of crystallization because the Sr and Rb concentrations are within the typical range for seawater (97.61 and 118.30 ppm for the Sr residue and leach and 0.2248 and 0.3490 ppm for the Rb residue and leach). The $^{87}Sr/^{86}Sr$ ratios from dolomite residue and calcite leach are 0.70796 and 0.70786 respectively, which suggests a terminal Cretaceous age, based upon comparisons with dated Sr isotope ratios (Fig. 6).

The dolomites dip slightly away from the center of the quarry and are much fractured. Minor faults with displacement of up to 1 m are spaced at about 5- to 10-m intervals. These faults do not cut the overlying strata but create a wavy contact between the dolomite and spheroid bed (Fig. 5). The deformation of the dolomites thus occurred prior to the deposition of the spheroid bed, which filled in depressions. The spheroids also occur in fractures up to 1 m wide to a depth of about 13 m (Fig. 4 and 5), and some fractures may have been open at the time of spheroid bed deposition.

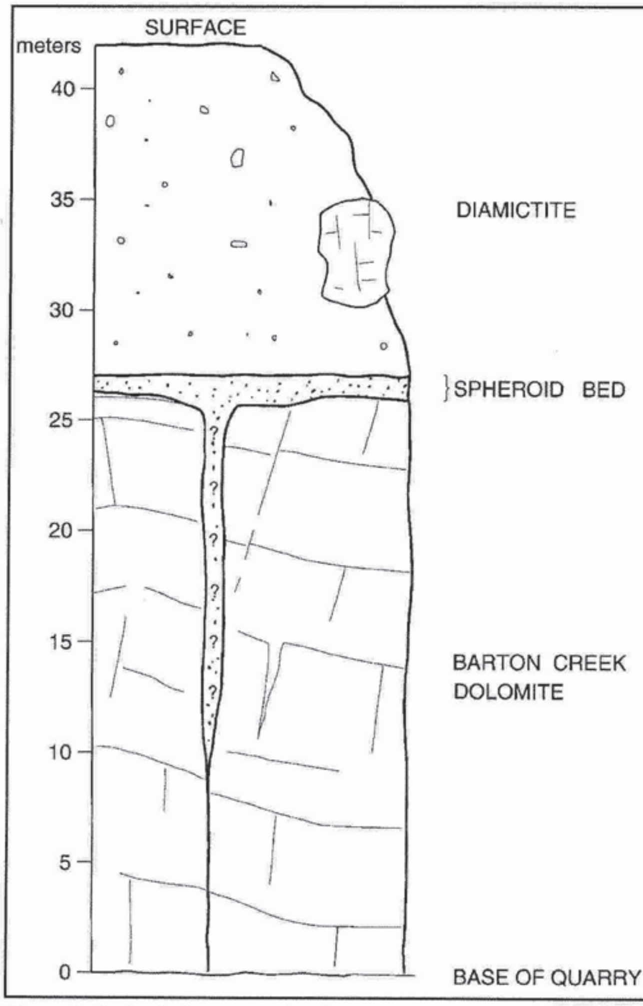

Figure 4. Geological cross section from the Albion Island quarry showing the three principal stratigraphic units: the Barton Creek dolomite and the Albion spheroid bed and diamictite.

THE SPHEROID BED

The spheroid bed is an informal name given to the 90- to 150-cm-thick member that lies between the Barton Creek dolomite and the overlying coarse Albion diamictite. The spheroid bed is heterogeneous, and although it contains rounded and angular clasts, its distinctive feature is the abundance of millimeter- to centimeter-size spheroidal bodies of dolomite and clay that we refer to as spheroids (Figs. 7 through 10). These spheroids are matrix supported in a weakly consolidated, clay-rich, fine-grained (10 to 40 μm) dolomite and calcite silt matrix.

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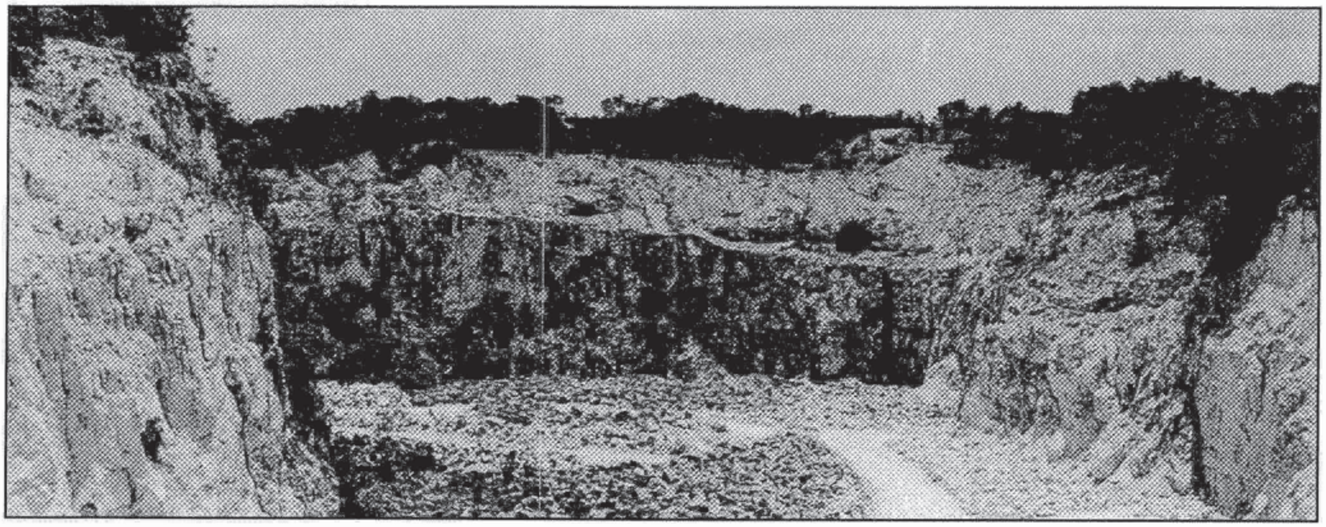

Figure 5. Albion Island quarry. Note the disconformity between the Barton Creek dolomite and overlying Albion Formation that extends around the quarry. Also note the abundant vertical fractures in the dolomite and the wavy appearance of the contact between the Barton Creek dolomite and spheroid bed.

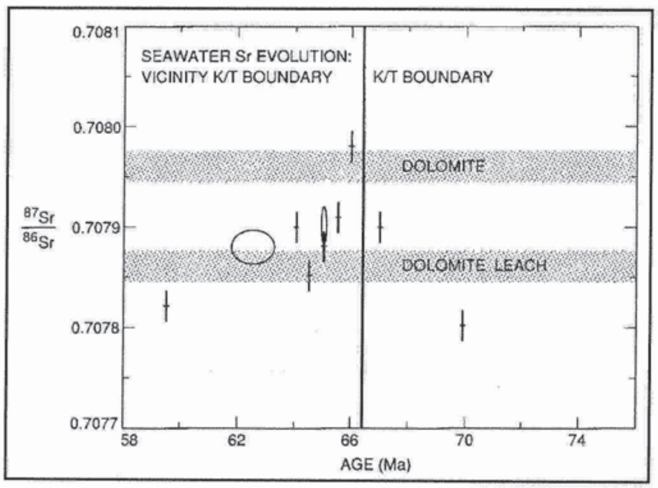

Figure 6. Results of strontium isotope analyses of the Barton Creek dolomite. Horizontal stippled bands give the $^{87}Sr/^{86}Sr$ values (1 sigma) for the whole dolomite and the dolomite leach (calcite removed with weak HCl). Sample is from a foraminifera-rich sample collected 1 m below the base of the spheroid bed. Bars (Hess et al., 1986) and ellipses (DePaolo and Ingram, 1985) give the global trend in $^{87}Sr/^{86}Sr$ values about the K/T boundary (vertical line), set by convention to 66.5 Ma.

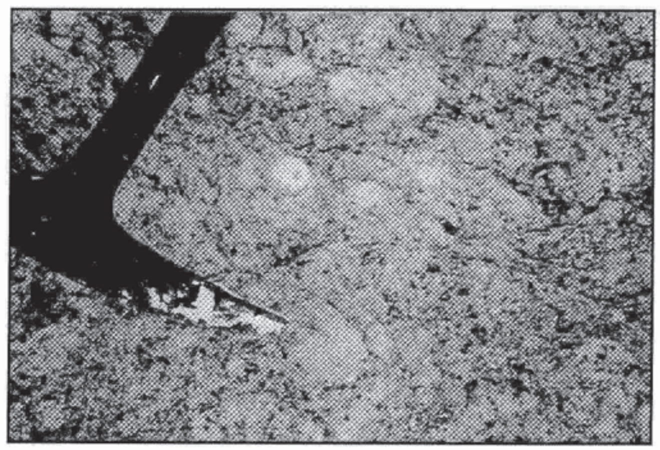

Figure 7. Spheroid bed outcrop. Note large dolomite spheroid (white) near center of photograph. Dark clasts are clay. Hammer handle width is 2 cm.

Detailed examination of four spheroid bed profiles indicates that as many as four layers are present. They are differentiated by varying amounts of clay and calcite and by mottled colors ranging from orange to pink to white. Boundaries between these layers are gradational. Field observations indicate that the percentages of clay and spheroids are variable but never exceed 50% of the bed (by volume). Clay-rich layers contain sheer planes with slickensides.

Dolomite spheroids with a modal diameter of 2 to 4 mm compose about 20 to 30% (by volume) of the bed (Fig. 8). Shapes range from spherical, to oblate spheroids, to triaxial ellipsoids, but include lumpy and subangular forms. Oblate shapes are more common near the base, where elongate forms lie roughly parallel to the basal surface (Fig. 8) and the spheroids appear to be squashed. The spheroids are finer grained than the matrix (Fig. 9). Large dolomite spheroids, 1 to 2 cm in diameter, compose about 1% of the bed. Some of these show concentric alternations of fine and coarse grain sizes or a coarser rind. The

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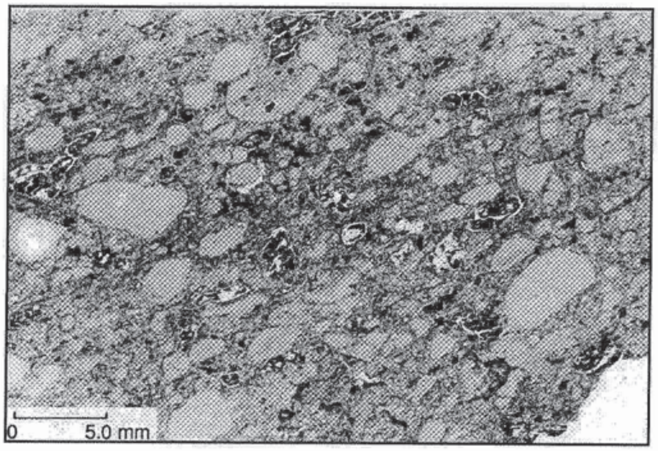

Figure 8. Thin section (natural light) of spheroid bed near base. Light-gray angular to spheroidal clasts are dolomite. Dark clasts with voids (white) are clay. Note alignment of clasts parallel to bedding (angled lower left to upper right in thin section) and apparent flattening of spheroids (oblate shapes).

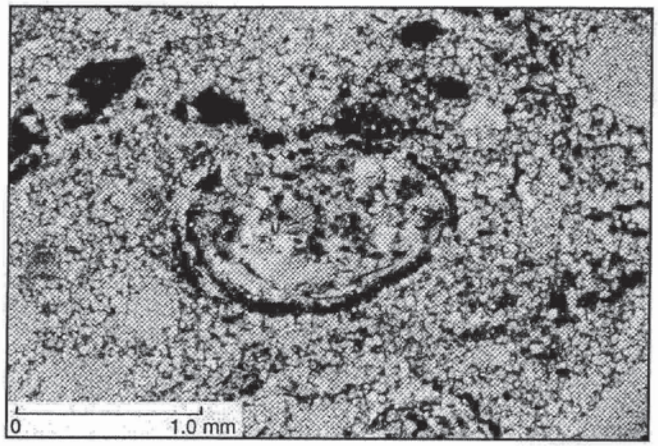

Figure 10. Thin section (crossed nicols) of clay spheroid from spheroid bed. Note void (black) around the spheroid, which is typical. Dark patches in center are nearly isotropic and transparent under natural light and may be partially devitrified glass.

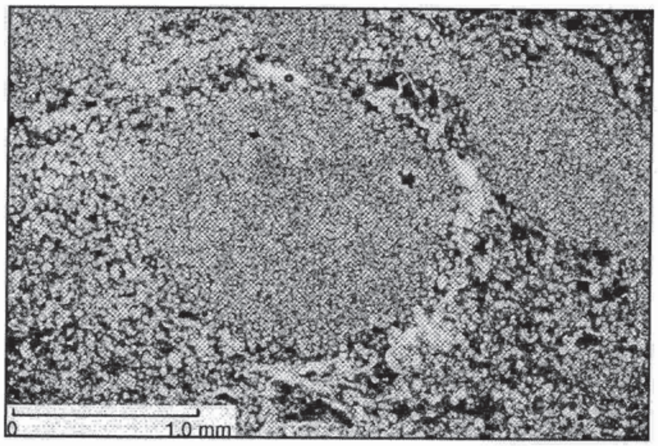

Figure 9. Thin section (natural light) of dolomite spheroid. Note that the spheroid is finer grained than the silt matrix.

upper portion of the spheroid bed contains about 1% dark-gray rounded to highly angular, fine-grained, 1- to 3-mm-diameter dolomite clasts, some of which are plastically deformed. These are absent from the lower portion of the bed.

The clay clasts also occur as spheroids (Fig. 10), but they are more commonly angular or lenticular bodies. Clay clasts are green, orange, and red in outcrop, with the variations in color often being a product of alteration (many green clasts have red or orange rims). The basal layer in all four profiles examined contains abundant, shiny, translucent green, flattened oblate, clay clasts. These clasts, like the dolomite spheroids, also appear to be squashed. At the basal contact, spheroids surround lumps of the underlying dolomite and appear "welded" to the dolomite surface.

THE DIAMICTITE

The upper member of the Albion Formation is a coarse diamictite containing rounded to highly angular carbonate clasts that range in size from less than 1 mm to about 7.5 m. The minimum thickness of this unit is 15 m, but since it extends to the surface we do not know the original thickness. The entire unit is matrix supported by weakly consolidated (except at the base) micritic dolomite silt in the 10-to 60-μm range. There is no clear indication of sorting, stratification, or grading. The basal contact is characterized by an abrupt occurrence of large clasts within a lithified matrix. Although the abrupt change in grain size and lithification gives the boundary a sharp appearance, in several locations there appears to be little change in the matrix composition across the boundary, and dolomite spheroids are present in the diamictite.

Clasts are commonly fractured, and those greater than 30 cm are always fractured (Fig. 11). The largest clast (7.5 m) found in the quarry has a grooved facet (Fig. 12). Many smaller clasts were found with polish and striations (Fig. 13), the latter in some cases in multiple directions on the same clast. We found one 3-m clast with a 7-cm-thick coating of dolomite mud (Fig. 11). Many of the smaller dolomite clasts, including those studied in thin section, also contain dolomite coatings or rinds. A cluster of rounded lumps of fine-grained dolomite ranging in size from 15 to 60 cm was also found (Fig. 14). These lumps have a few dolomite clast inclusions and are very similar to the mud balls reported from alluvial fan mudflow (debris flow) deposits (e.g., Bull, 1964). In one location we found a 2 m × 1 m exposure of a pocket of radially fibrous calcite spheres (pisoids) (Fig. 15). Most of these pisoids are about 1 cm in diameter, but a few are smaller and form amalgamated masses.

Thin sections (Fig. 16) of the fine fraction of the diamictite demonstrate that many of the observations made at the outcrop

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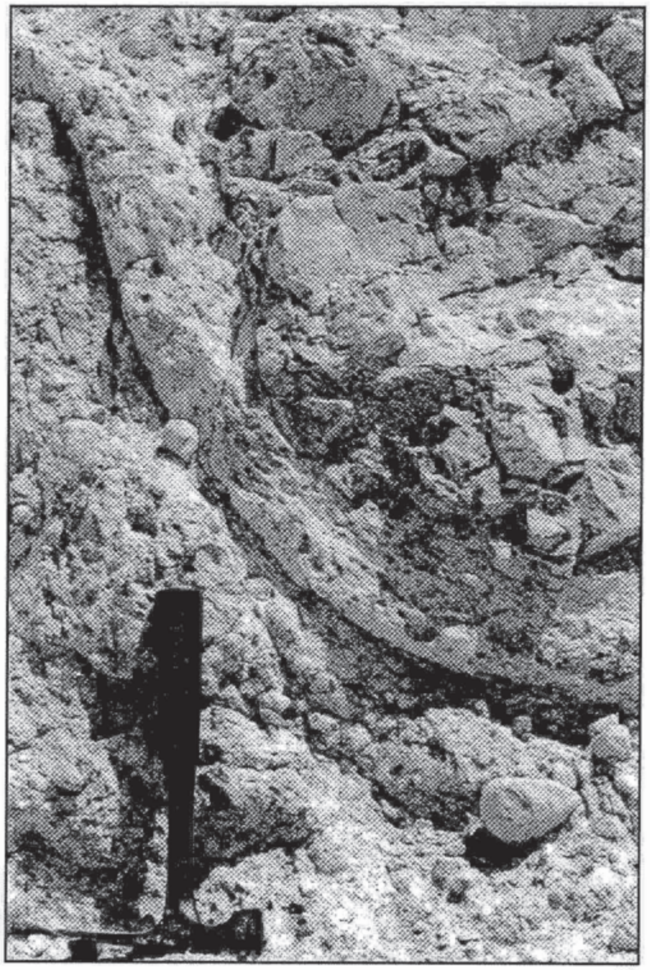

Figure 11. Edge of 3-m-diameter dolomite clast. Note extensive fracturing and 7-cm-thick mud coating. Albion diamictite. Hammer 30 cm long.

Figure 12. Right half of 7.5-m-diameter dolomite clast (outlined in black for clarity) showing faceted and grooved surface on upper right of clast. Albion diamictite.

also occur at the microscopic level. Millimeter-sized clasts are also poorly sorted, rounded to angular, and matrix supported and include breccia clasts and dolomite clasts with rinds of coarser dolomite (Figs. 16 and 17). There is commonly a void between clasts and the surrounding matrix (Fig. 16), which in some cases retains gypsum filling. Some clasts contain dark, presumably carbonaceous, cores that are rounded and sharply bounded and may be replacement features, although similar dark dolomites occur as individual spheroids (Figs. 16 and 17). Thin-section analysis of one of the mud balls noted above shows that it is composed of fine-grained euhedral dolomite and an unidentified silicate, possibly a member of the palygorskite group, along with sparse authigenic quartz.

All of the medium to large (greater than 15 cm) clasts we examined in the field are a dolomite that is not notably different from the underlying dolomite in the quarry. Thin sections, however, reveal minor components of clearly exotic carbonate clasts that have sedimentary textures or fossil preservation markedly different from the underlying Barton Creek dolomite (Fig. 18). One such clast of limestone contains rudist (*Sellaea* sp.) fragments of Barremian to Albian age (Erle Kauffman, personal communication, 1994). Another contains foraminifera (*Nezzatinella piccardi*) of Albian to early Campanian age (Richard Boettcher, personal communication, 1993). These limestones must have come from more than 1 km below the Cretaceous surface of the Yucatán platform and are exposed nowhere near this region. Similar limestones are reported from the deep drilling near the Chicxulub crater (Marshall, 1974; Weidie, 1985), and we interpret these clasts as primary ejecta from the Chicxulub crater.

Authigenic quartz crystals up to 4 cm long and commonly intergrown with carbonate are found in the diamictite. Acid leach residues of the diamictite matrix yielded an authigenic quartz grain with serpentine inclusions (Fig. 19) and two granitic clasts (Fig. 20). Other quartz clasts contain Class 1 deformation features (Robertson et al., 1968), such as irregular planes of inclusions and undulatory extinction, but we observed no definitive evidence of shock metamorphism.

The most abundant clast type that we interpret as exotic is

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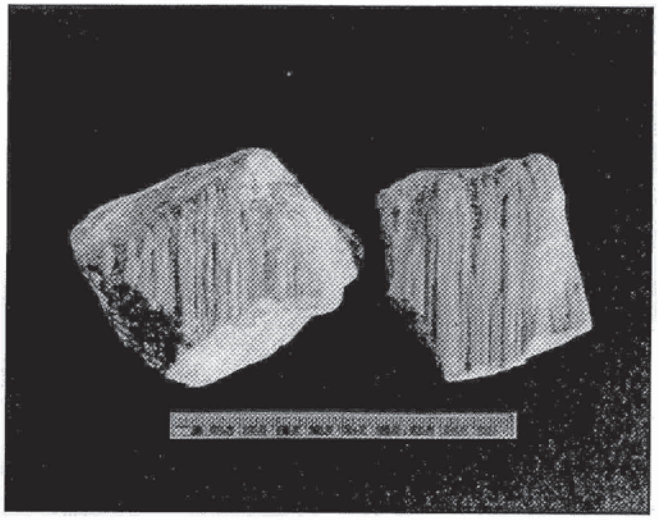

Figure 13. Striated dolomite clasts. Albion diamictite.

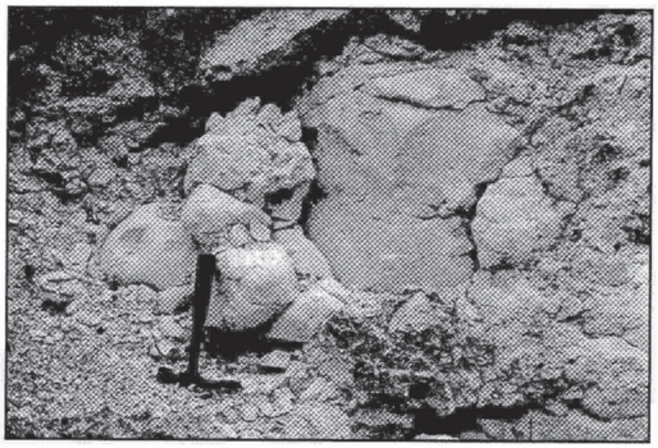

Figure 14. Dolomite mud balls. Albion diamictite. Hammer 30 cm long.

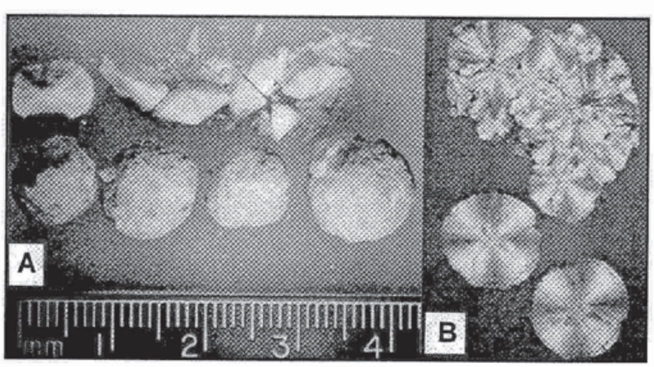

Figure 15. Calcite pisoids. A, whole and fractured pisoids showing fibrous radial structure. B, thin section (crossed nicols) showing radial structure of single pisoids and amalgamated clusters. Albion diamictite. The origin of the pisoids is uncertain, but they may be the product of hydrothermal activity (see Addendum).

clay. Clay clasts compose 1 to 10% of the diamictite by volume as measured in thin section. A 10% clay abundance by weight was measured from the acid leach of a kilogram sample. Nontronite, a common alteration product of glass, was identified with X-ray diffraction. Thin sections show the presence of a variety of clay minerals, of which smectites appear most abundant. We interpret these clay clasts as altered glass. Many of the clay clasts have vesicular structure, and a few retain the optical properties of glass (Figs. 21, 22, and 23). Although exotic clasts are critical to our interpretation of the diamictite unit, they may comprise no more than 10% of the unit, depending upon the source of the large population of dolomite clasts.

The weakly consolidated dolomite silt matrix in the diamictite and spheroid bed presents a special problem. The grains are individual rhombs: some have sharp corners; others are rounded. Such dolomite silts have been reported from the deep-sea floor and occur locally on carbonate platforms as solution residues of dolomitic limestones (Fischer, 1953), but no other large-scale occurrence is known to us.

COMPARISONS AND CORRELATIONS

We propose that the disconformity between the Barton Creek dolomite and spheroid bed represents the K/T boundary. Our placement of the boundary is based upon our interpretation of the Albion spheroid bed and diamictite as Chicxulub impact ejecta, since no Tertiary sediments are exposed at the quarry. We correlate the spheroid bed with the spherule beds reported from K/T sections elsewhere in the Gulf Coast and Caribbean region (e.g., Hildebrand and Boynton, 1990; Izett, 1991; Maurrasse and Sen, 1991; Smit et al., 1992, 1994; Pitakpaivan et al., 1994). We chose the name spheroid bed to emphasize that it is not identical to the previously described spherule beds. We correlate the Albion diamictite with the coarse detrital unit interpreted as the "continuous deposit" of ejecta and scoured surface debris found on the rim of the Chicxulub crater (Pope et al., 1993).

The closest comparison for the Albion Island spheroid bed is the spherule bed described from Mimbral (Smit et al., 1992). The Mimbral bed varies from 0 to 100 cm thick and is composed of 20% to more than 90% calcite and chlorite-smectite spherules with relict vesicles, along with subangular to subrounded limestone clasts similar in size to the spherules. Some of these clasts are plastically deformed. Most of the spherules at Mimbral range from 1 to 5 mm. Even though all of these characteristics have parallels in the Albion Island spheroid bed, there is a notable absence of dolomite at Mimbral. The Mimbral bed apparently does not contain the large centimeter-sized spheroids found at Albion Island; however, centimeter-sized spherule fragments are reported from Haiti (Hildebrand and Boynton, 1990; Hildebrand, 1993). The fabric of the Albion spheroid bed is similar to the imbricated fabric reported for the melt ejecta layer in K/T boundary deposits in the western interior of North America (Pollastro and Bohor, 1993), although the Albion fabric appears to be mostly the result of diagenic flattening.

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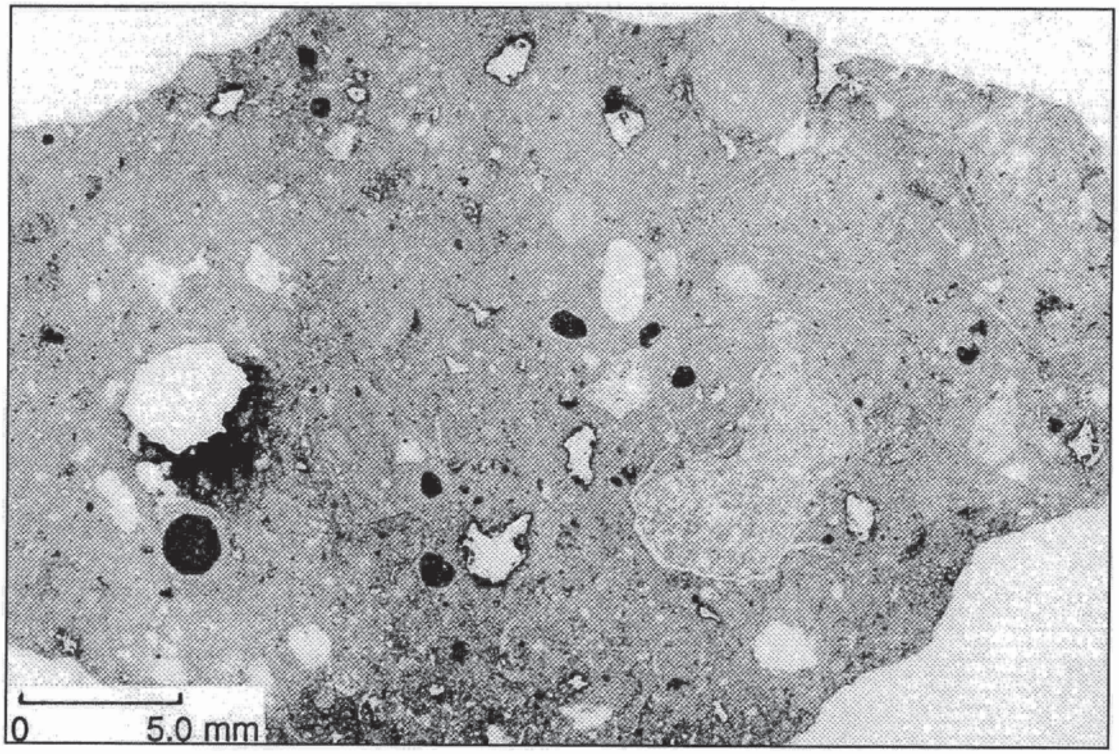

Figure 16. Thin section (natural light) of diamictite sample. Note variety of clasts, several with voids (thin white bands) around clasts, and dark dolomite spheroids (also shown in Fig. 17). These dark spheroids also occur within clasts and may be secondary replacements.

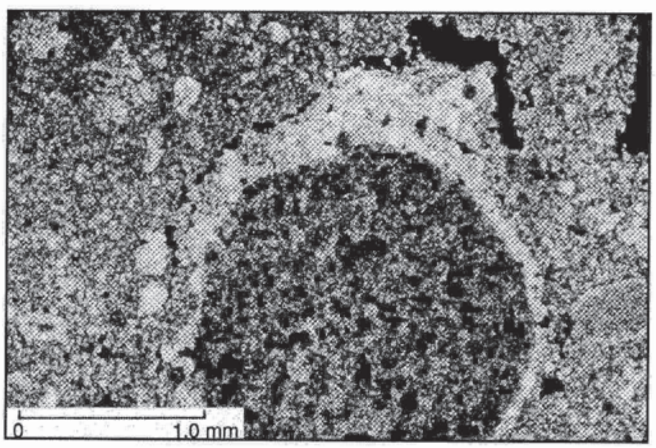

Figure 17. Thin section (crossed nicols) of dark, carbonaceous (?) dolomite spheroid with dolomite rind. Albion diamictite.

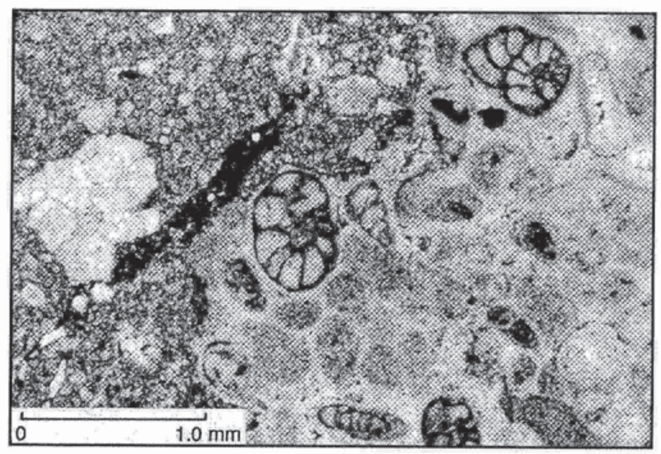

Figure 18. Thin section (natural light) of fossiliferous limestone clast. Albion diamictite.

The clay spherules from the Gulf Coast and Caribbean sites are interpreted as altered tektites (Hildebrand and Boynton, 1990; Izett, 1991; Maurrasse and Sen, 1991; Smit et al., 1992; Pitakpaivan et al., 1994), but spherical clay clasts are much more common at those sites than at Albion Island. We interpret the clay clasts with relict vesicles and rare devitrified glass shards from the Albion Island spheroid bed and diamictite as impact glass, but their shapes compare better with the "Flädle" in suevite glass from Ries crater (e.g., Hörz, 1965) than with tektites. Similar observations have been made for clay clasts in well Y-2 from the upper portion of the ejecta drilled on the rim of the Chicxulub crater (Hildebrand et al., 1991). There is, however, a

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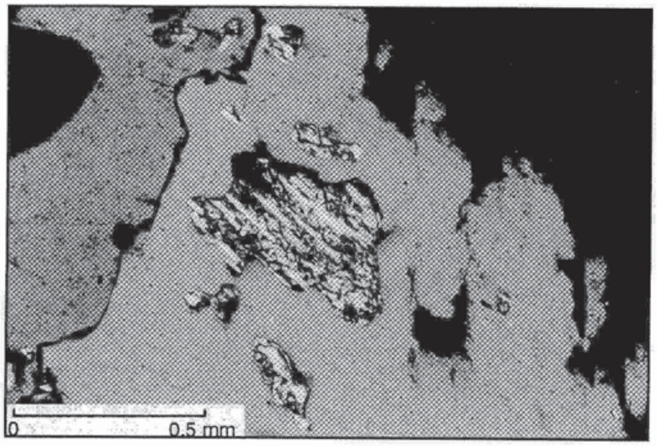

Figure 19. Thin section (crossed nicols) of authigenic quartz grain with serpentine inclusions. Albion diamictite.

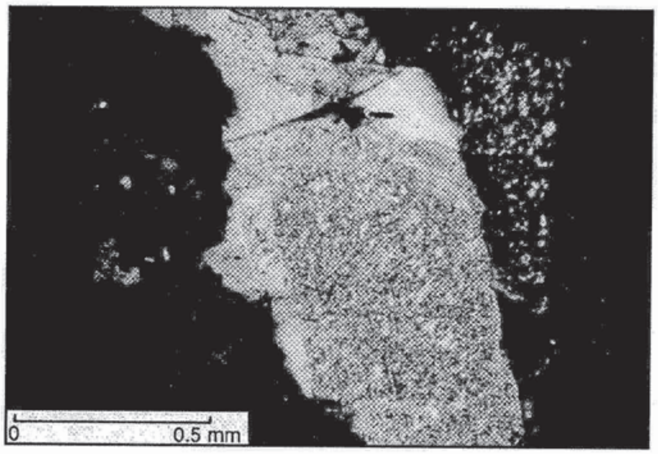

Figure 20. Thin section (crossed nicols) of granitic schist clast. Albion diamictite.

discrepancy in size: The smallest "Flädle" from Ries correspond to the larger Albion examples. Kieffer and Simonds (1980) suggest that impacts into carbonate targets produce a rapid expansion of gases that disperses large amounts of melt with the ejecta. The abundant clay clasts in the Albion deposits may represent such a process. The fact that classic tektite forms are rare at Albion Island may reflect the much shorter trajectory of the Albion glass, given its proximity to Chicxulub.

The dolomite spheroids, which make up most of the spheroids at Albion Island, may include clasts rounded by abrasion, but others have concentric structures that imply accretionary growth. These spheroids with concentric zones of fine and coarse dolomite resemble the accretionary lapilli from Ries, which have similar concentric structures that may have formed in a water-rich vapor plume (Graup, 1981). We suggest that some if not most of these spheroids are the tektite equivalent of shock-heated carbonates and sulfates, present in the upper Chicxulub target rocks. Such heating would drive off CO_2, SO_3, and SO_2, producing large amounts of quicklime (CaO, and possibly MgO) (Brett, 1992; Sigurdsson et al., 1992; Pope et al., 1994; Ivanov et al., this volume). This quicklime may have formed spheroids in the vapor plume. The dolomite spheroids may have precipitated directly from the plume through the reverse reaction between the oxides and the CO_2 produced. Such a scenario has been proposed for carbonates found in the Haughton impact crater in Canada (Martinez et al., 1994). Similarly, the dolomite silt in the Albion deposits may have formed by nucleation of dolomite in the cooling vapor plume.

An alternative explanation is that the dolomite spheroids formed after deposition through diagenesis of spheroids composed of the highly unstable Ca and Mg oxides. The flattening of the dolomite spheroids, most evident at the base of the bed, suggests that the transition from oxide to the now hard, crystalline carbonate may have succeeded emplacement. The dolomite spheroids with rinds may be carbonate clasts that were calcined on the surface but not completely degassed. CO_2 depletion has

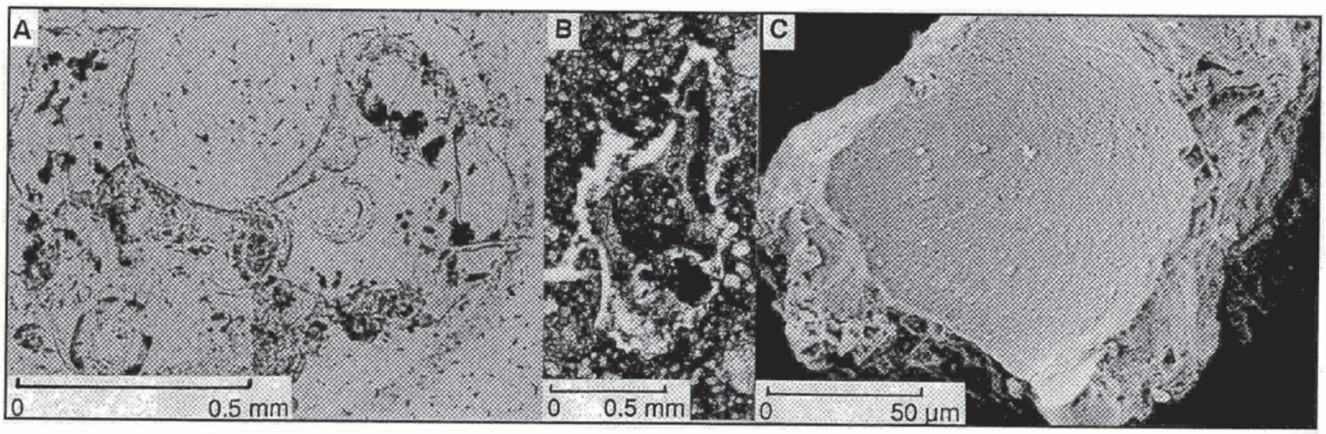

Figure 21. A, thin section (natural light) of devitrified, vesicular glass shard. B, thin section (natural light) of dolomite-filled vesicle in clay clast. C, electronmicrograph of a clay clast vesicle interior. Albion diamictite.

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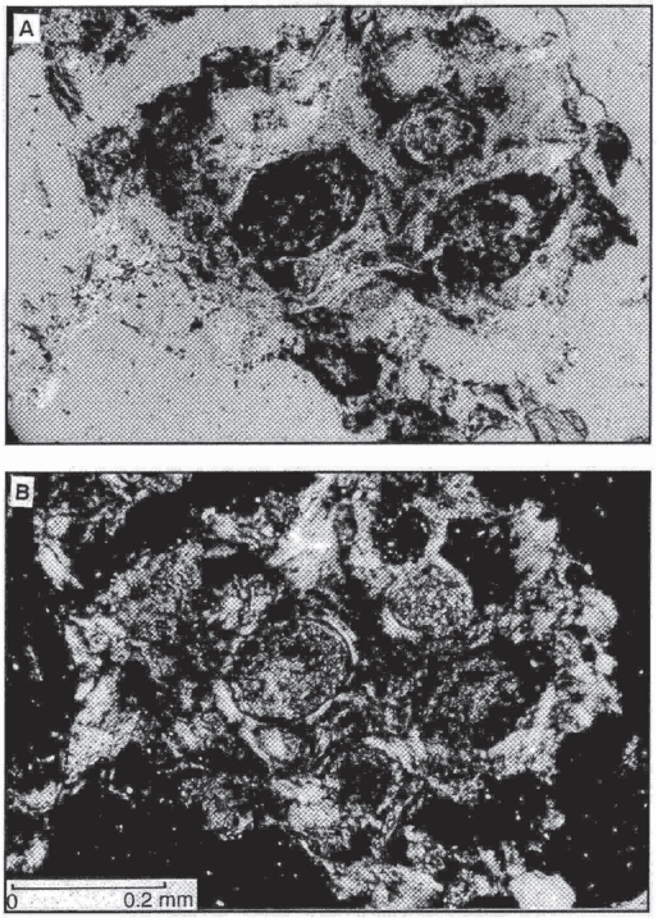

Figure 22. Thin section of vesicular shard: A, natural light; B, crossed nicols. Note that some portions of the shard are isotropic (translucent regions in A are completely dark in B) and may be mostly glass. Bright areas in A are clay, which also fills most of the vesicles. Albion diamictite.

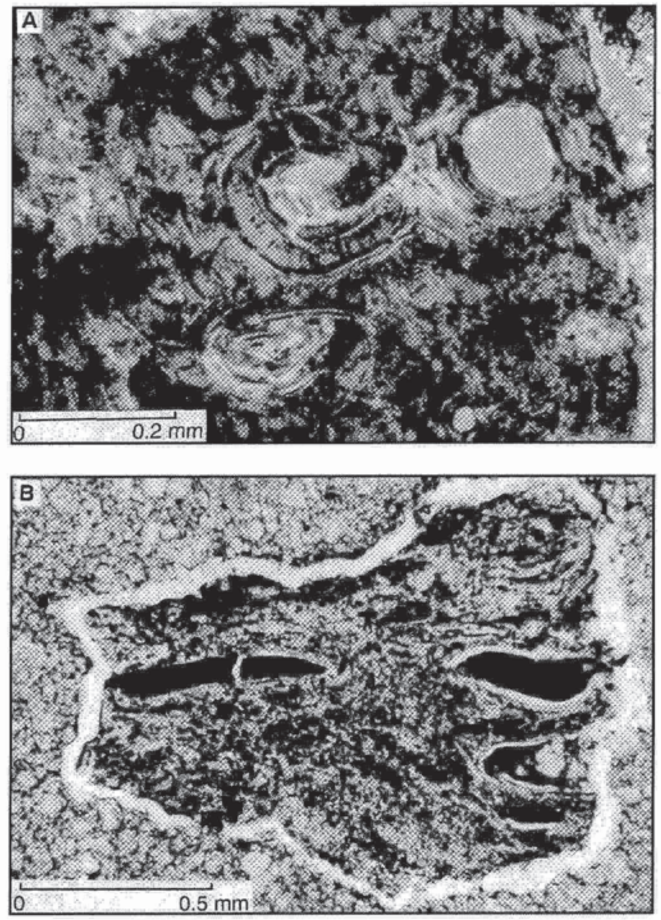

Figure 23. Thin sections of altered vesicular shards in natural light. Note squashed vesicles in A and B and concentric and radial growths of clay minerals partially filling vesicles in B. Albion diamictite.

been proposed for the origin of reaction rims around limestone clasts at Ries crater (Kieffer and Simonds, 1980). These rinds, like the quicklime spheroids, would have altered back to carbonate.

The Albion diamictite is petrographically similar to the approximately 600-m-thick coarse detrital unit recorded in petroleum exploration drilling on the rim of the Chicxulub crater, originally described as the detrital anhydrite facies (Marshall, 1974; Weidie, 1985). Thin sections from the Chicxulub and Albion deposits (Fig. 24) show very similar texture and composition; for example, both contain rounded and angular clasts floating in a dolomite silt matrix. Major differences at Chicxulub are the abundance of anhydrite, which is nearly absent at Albion Island, and the paucity of clay clasts, which are abundant at Albion Island. Previously (Pope et al., 1993), we interpreted the Chicxulub detrital deposit as the "continuous deposit" resulting from ballistic sedimentation as described by Oberbeck (1975). This interpretation was tentative, however, since the Chicxulub deposits are known only from drilling with limited sampling and macroscale features are unknown.

The Albion diamictite provides a more complete picture of the Chicxulub ejecta blanket, exposing a facies comparable to the well-studied Bunte breccia of the Ries crater (Hörz et al., 1977; Chao et al., 1978; Hörz and Banholzer, 1980; Hörz et al., 1983). Important characteristics of the Bunte breccia apparently shared by the Albion diamictite are as follows: (1) they are extremely poorly sorted (clast sizes range over eight orders of magnitude for Bunte and five orders for Albion); (2) they are totally chaotic with no stratification (indicative of turbulent flow); (3) the distal sections contain greater than 90% local material (most of the large Albion clasts may be local, but this is not confirmed); (4) breccias within breccias; and (5) there are clasts with striations, polish, and possible hinge fractures. Although highly shocked clasts (greater than 10 GPa) occur at Ries, they are rare: less than 0.1% by weight. None have been found in the Albion diamictite.

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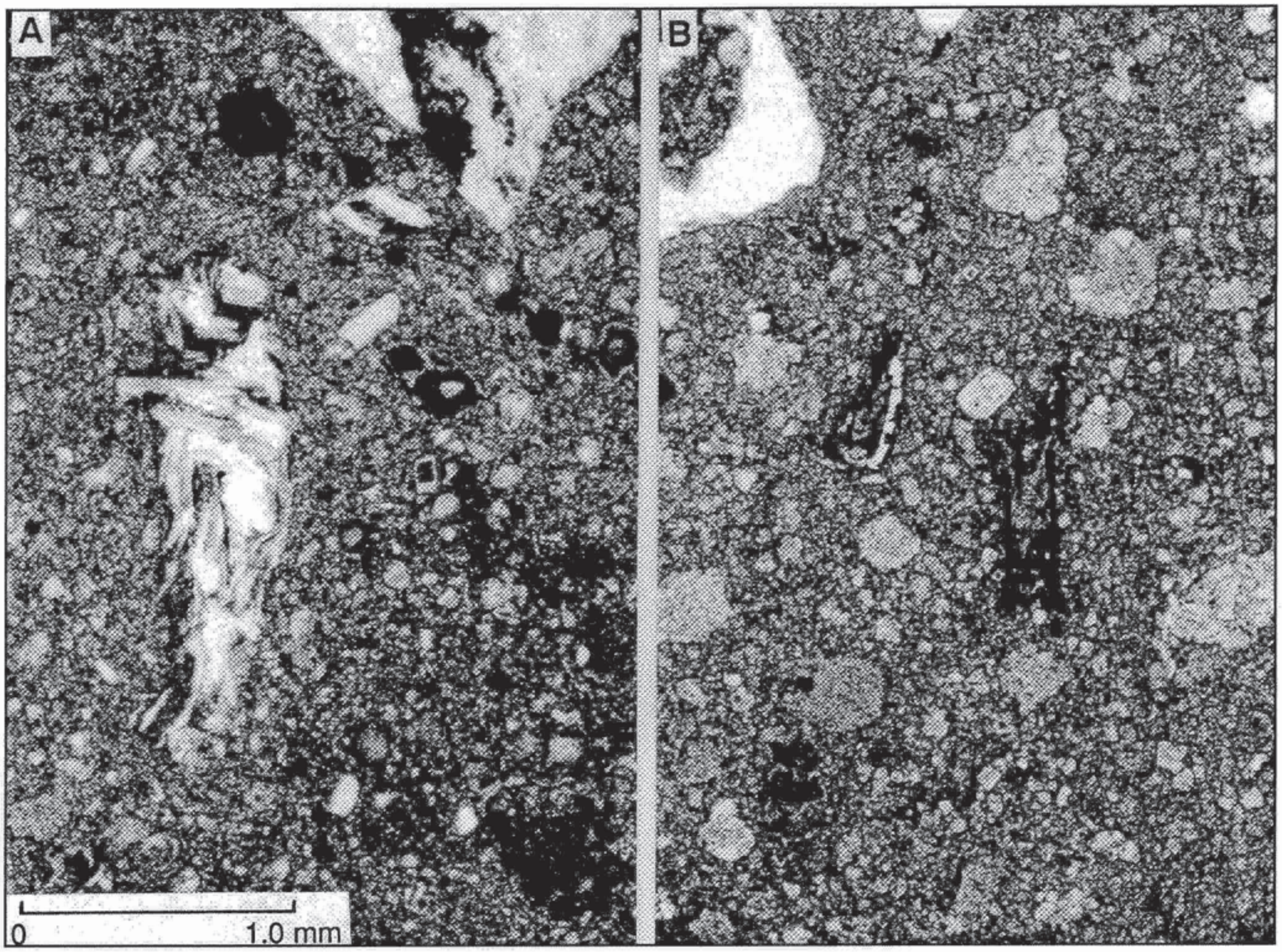

Figure 24. A, thin section (crossed nicols) of ejecta blanket sample from Yucatan 2 well, located about 130 km from Chicxulub crater center. Depth 700 m (sample Y2 N11). B, thin section (natural light) of Albion diamictite sample. Note similarities in clast sizes and morphologies. Both samples have dolomite silt matrix. Large clast near the center of A is anhydrite and in B is clay, illustrating the main compositional differences between the two deposits.

All of the above characteristics are either consistent with or indicative of ballistic sedimentation processes, as argued by Hörz and his colleagues (Hörz et al., 1977; Hörz and Banholzer, 1980; Hörz et al., 1983). Nevertheless, the preservation of the spheroid bed beneath the diamictite indicates that emplacement of this member at Albion Island did not involve secondary impacts or turbulent flow with any erosive power. This subject is discussed in more detail in the next section.

DEPOSITIONAL PROCESSES AND THE K/T EVENT

We propose the following sequence of events following the Chicxulub impact that are recorded in the sediments on Albion Island. We begin with a carbonate platform containing extensive interbedded evaporites. By analogy with other platforms, such as the Bahama-Florida platform, we may assume that this one oscillated between shallow marine, hypersaline evaporitic, and emergent conditions leading to freshwater incursions and that much of the carbonate was converted to dolomite relatively soon after deposition. The Albion Island location was surrounded by shallow seas receiving very little clastic sediment, hundreds of kilometers from any land mass with significant relief (Bateson and Hall, 1977). The first event was the air blast from the leading edge of the expanding vapor plume that may have stripped away surficial sediments, soil, or water, exposing foraminifera-bearing lagoonal carbonates that were probably already dolomitized. This event probably began about 10 sec after impact, judging from the proposed greater than 30 km/sec velocities for the initial blast proposed by Melosh (1989). The velocity of the expanding plume can surpass that of the impactor because gas expansion

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adds an additional velocity component. Although the bulk of plume traveled upward, spreading out on top of the atmosphere, the initial expansion may have been quasi-equidirectional until atmospheric drag slowed the lateral blast (Melosh, 1989; Vickery and Melosh, 1990).

The next event was the arrival of the seismic shock wave from the impact. This may be recorded by the fractures in the Barton Creek dolomite. Fracturing would have happened in less than a minute after impact and may have been more or less contemporaneous with the onset of spheroid deposition. The spheroid bed was probably deposited in a few minutes, as the main body of the vapor cloud passed over the site with an average velocity estimated at about 10 km/sec (Melosh, 1989). Expanding vapors would accelerate rapidly and quickly "outrun" the ballistic ejecta. As the superheated cloud passed through the early stages of the ejecta curtain it may have entrained the smaller clasts (Vickery, 1986), perhaps abrading and calcining the outer portions of the carbonate clasts to produce the large spheroids with rinds.

The last event recorded on Albion Island is the deposition of the Albion diamictite. We interpret the diamictite as having originated through a combination of ballistic and debris flow sedimentation. The presence at Albion Island of carbonate clasts from deep in the Yucatán platform indicates contribution of debris by ballistic sedimentation. Nevertheless, the preservation of the underlying spheroid bed argues against any secondary impact scouring at Albion Island but does not preclude the possibility that secondary impacts occurred nearby. The diamictite is probably a debris flow deposit that, initiated by ballistic sedimentation, continued to flow great distances, partly because of the abundance of dolomite mud and water in the matrix. The Albion diamictite contains large boulders floating in a mud matrix, mud balls, mud coatings on clasts, and minimal erosion at its base, all common characteristics of debris flow deposits. Rampino (1994) recently summarized the debris flow–like character of ballistic ejecta deposits. Hörz and Banholzer (1980) argue that turbulent flow can extend as much as a crater radius beyond ballistic termination. The Albion diamictite may be similar to the fluidized ejecta blankets on Mars.

Albion Island, 364 km from the center of Chicxulub, lies near the theoretical limit (Melosh, 1989) of continuous deposition and significant secondary cratering for either the 240-km or 300-km-diameter proposed for Chicxulub by Pope et al. (1993) and Sharpton et al. (1993) respectively. The island lies 100 to 200 km beyond this limit for the 170- to 180-km-diameter crater proposed by Hildebrand and colleagues (Hildebrand et al., 1991; Pilkington et al., 1994). Although the location of the Albion diamictite with respect to Chicxulub is consistent with all three crater diameters noted above, rather extensive fluidized flow must be invoked for the smaller diameter. Given the debris flow character of the diamictite, such long-distance flow is clearly reasonable.

CONCLUSIONS

Seismic disruption of basal sediments and spherule deposition occurred throughout the Gulf of Mexico region (Smit et al.,1994) and appear to be the hallmarks of early-stage, proximal events following the Chicxulub impact. Distal ejecta are characterized by two distinct stratigraphic units. The lower unit, called the "ejecta" or "melt ejecta" layer, contains spherules, altered glass shards, and other impact debris; the upper unit, called the "fireball" layer, contains abundant shocked quartz and is rich in siderophile elements, most notably iridium (e.g., Hildebrand and Boynton 1990; Hildebrand 1993; Pollastro and Bohor, 1993). Although the origin of this two-part stratigraphy is controversial, arguments have been presented that the lower bed contains ejecta of limited distribution that was wholly or partially ballistically emplaced and that the upper bed contains globally distributed material from the vapor plume originally deposited on top of the atmosphere (Hildebrand and Boynton, 1990; Hildebrand, 1993; Pollastro and Bohor, 1993).

The spheroid bed on Albion Island may be the proximal equivalent of the lower "ejecta" layer. Nevertheless, we suggest that this spheroid bed contains ejecta entrained by the laterally expanding vapor plume, and possibly material precipitated from the rapidly cooling plume, but little material deposited along ballistic trajectories. The spheroids and associated debris traveled faster than, and were detached from, the main ejecta curtain, thus explaining their stratigraphic position beneath the bulk of the ballistic ejecta (Albion diamictite), which arrived later. Whether or not this scenario applies in toto to the widely distributed "ejecta" layer is uncertain; however, given that the Chicxulub impact into a nearly 3-km-thick sequence of evaporites and carbonates released over a trillion tons of CO_2, SO_3, SO_2, and water vapor (Pope et al., 1994; Ivanov et al., this volume), we propose that the importance of volatiles in the formation and transport of the ejecta has been greatly underestimated.

The Albion diamictite is the distal portion of the true ejecta blanket as defined by Melosh (1989, p. 89). The ejecta blanket is the zone of thick, continuous deposition that surrounds most craters and is distinct from more distal ballistic ejecta deposits. The Albion Island site may be near the limit of the ejecta blanket distribution (reconnaissance of the region in 1994 and 1995 failed to locate any other examples). The Albion diamictite is an extension of the thick detrital unit drilled on the rim of the Chicxulub crater, but it is genetically distinct from other K/T boundary breccias and coarse deposits reported from the Chicxulub vicinity, which are probably slump deposits (e.g. Alvarez et al., 1992; Hildebrand et al., 1994; Montanari et al., 1994).

The globally distributed "fireball" layer that typically caps K/T boundary deposits is not present at Albion Island, where the sequence is truncated by the surface. Evidence of other late-stage impact processes, such as those related to impact waves,

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are similarly absent. Nevertheless, the Albion Island section is thus far unique in its record of the early stages of the Chicxulub impact event. Future work at the Albion Island quarry will no doubt produce many more insights into the final seconds of the Cretaceous and the process of large impacts on Earth.

ADDENDUM

Ongoing studies at the Albion Island quarry have added important new information, which we briefly summarize below.

The Late Cretaceous age of the dolomite underlying the Albion spheroid bed has been confirmed by fossils. A fossiliferous limestone lens within the dolomite yielded nerineid gastropods showing infolded wall patterns characteristic of the latest (Campanian-Maastrichtian) members of the family (Jan Smit, personal communication, 1995). The same lens contains fossil crabs of a new species, *Carcineretes planetarius,* a genus that is also restricted to the Upper Cretaceous, probably Maastrichtian (personal communication, Francisco Vega Vera and Rodney Feldmann, 1995).

Two recent observations suggest that Albion Island was subaerial at the time of the Chicxulub impact: (1) caliche deposits are found in several locations just below the spheroid bed, capping the Barton Creek dolomite, and (2) the apex of an anticlinal fold in the Barton Creek dolomite was eroded slightly before deposition of the ejecta, indicating that uplift occurred prior to the impact.

It has also become clear that the Albion diamictite contains evidence of hydrothermal activity. Hydrothermal alteration appears concentrated in one area of the quarry a few hundred square meters in size, where authigenic quartz is found in vugs and in veins within clasts. Spheroidal intergrowths of fibrous quartz, calcite, and fibrous palygorskite occur in pockets in this zone and are probably the product of circulating hot fluids. The calcite pisoids described above may also be of hydrothermal origin. Brecciated and recemented clasts are associated with the authigenic quartz, possibly the product of steam explosions. Authigenic quartz, possibly also of hydrothermal origin, is present in the underlying Barton Creek dolomite, which suggests that the hydrothermal activity may not be restricted to the ejecta deposits. The timing of the hydrothermal activity remains uncertain. Conceivably hot fluids circulated in the ejecta as it cooled, or the seismic shock of the impact may have triggered local hydrothermal activity, but equally well the hydrothermal overprint may be much younger and unrelated to the impact.

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NOTE ADDED IN PROOF

Further study has shown that the radially fibrous calcite "pisoids" are more widely distributed in the ejecta. Blocks of carbonate composed of interlocked spheroidal to asymmetrical radial bodies are incompatible with accretionary pisolite growth and suggest quench crystallization from carbonate melt. Continuing field studies have identified additional coarse ejecta deposits 100 km farther south in central Belize.

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